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Multidecadal streamflow regimes in the interior western United States: Implications for the vulnerability of water resources

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Abstract. In the interior western United States, increased demand for water coupled with the uncertain nature of anthropogenic and natural hydroclimatic variations add challenges to the task of assessing the adequacy of the existing regional water resources systems. Current availability of relatively short instrumental streamflow records further limits the diagnosis of multidecadal and longer time variations. Here we develop a long-term perspective of streamflow variations using a 285-year long tree-ring reconstruction at Middle Boulder Creek, Colorado. Analysis of the reconstructed streamflow provides useful insights for assessing vulnerability: (a) a wider range of hydrologic variations on multidecadal time scales, not seen in the instrumental record, (b) wet/dry regimes show disparate fluctuations across various flow thresholds, and (c) temporal changes in the flow probabilities have varied "flavors" corresponding to wet and dry regimes and their spatial extent. Based on these results, we discuss implications for the climate-related vulnerability of regional water resources.

Introduction

Regional freshwater resources exhibit varying degrees of sensitivity to the climate variations and change. While the large-scale climate influences on year-to-year streamflow variations have been recognized [e.g., *Cayan and Peterson,* 1989], investigations into the multidecadal streamflow variations have been stymied by the lack of long streamflow records. Consequently, the current understanding of issues related to water resources planning and management is limited by the relatively short-length (typically 30-50 years) of hydrologic records. It has also been noted recently [*IPCC,* 2001], *"There are apparent trends in streamflow volumes – increases and decreases – in many regions. However, confidence that these trends are a result of climate change is low because of factors such as the variability of hydrological behavior over time, the brevity of instrumental records, and the response of river flows to stimuli other than climate change."* Therefore, a reliable diagnosis of the sensitivity of regional water resources to future climate change and variations is in part dependent on a better understanding of the range of natural hydrologic variations derived from multiple natural archives (such as tree-rings) that help augment the limited length instrumental records. In this letter, we use a 285-year tree-ring based streamflow reconstruction for the Middle Boulder Creek, Colorado, to develop a long-term perspective of the low and high streamflow regimes on multidecadal time scales. In the following sections, the reconstruction is described, changes in the empirical flow probabilities at multidecadal time scales and associated "flavors" of high and low flow regimes are examined, and their implications for assessment of the regional water resources vulnerabilities discussed.

Data and Study Region

In regions where moisture is limiting to tree growth, tree rings have been found to be useful proxies of past hydrologic variations [e.g., *Stockton and Jacoby*, 1976; *Meko et al.*, 1995]. The Middle Boulder Creek streamflow reconstruction used in this study was generated using stepwise regression to predict mean annual streamflow from a set of moisture-sensitive Front Range tree-ring chronologies. The regression model, with four variables, explained 70% of the variance in the instrumental record for the calibration period, 1950-1980. Spectral analysis of the residuals from the reconstruction procedure shows that variance is concentrated within the interannual band. *Woodhouse* [2001] details the methodology and testing for the streamflow reconstruction. The final reconstruction extends from 1703 to 1987 and indicates variations at interannual and interdecadal time scales (Figure 1).

The Middle Boulder Creek watershed is located in the South Platte River Basin. This predominantly snowmelt-driven river drainage contributes to the water supply for the City of Boulder and irrigation for local agricultural enterprises. Middle Boulder Creek mean annual streamflow is highly correlated with other South Platte Basin streams [*Woodhouse*, 2001], indicating a large-scale climate influence on regional streamflow, and suggesting that these results are applicable to other streams in the basin.

Multidecadal Streamflow Variations

We use the Middle Boulder Creek streamflow reconstruction to explore multidecadal high and low flow regimes, and the extent to which water excesses and deficits are manifested across various flow thresholds (flow levels based on some key percentiles: 10%, 33%, 67%, 90%). The reconstructed streamflow shows several notable periods of persistent low streamflow during the 19th century (Figure 1). These are followed by a high streamflow period in the early 20th century that has also been noted in a number of previous studies [e.g., *Stockton and Jacoby,* 1976]. These persistent streamflow anomalies on multidecadal time scales provide striking examples of the wider range of natural hydroclimatic variations not seen in the late 20th century instrumental records. However, the severity of these multidecadal low and high streamflow periods depends on the year-by-year sequence of flow anomalies during these regimes. This is especially relevant in the context of the vulnerability assessment of the existing water resources systems – for example, the management and planning during droughts may differ based on the relative differences in the anomalous flow sequences and their associated empirical flow probabilities across various thresholds. Thus, the anatomy of multiyear droughts is dependent not only on the mean magnitude of the anomaly, but the relative frequency with which annual flow anomalies of differing severity contribute to the accumulating deficits. Exploring the temporal variations in empirical probability density functions across key thresholds during multidecadal periods of low and high streamflow can provide a broader view of the level of stress exerted on the water resource management infrastructure and the numerous sectors that depend on it. Further, temporal changes in the streamflow distributions reflect the regional expression of climate variations on multiple time scales, and the nonlinear and epochal nature of teleconnections [*Hoerling et al.,* 1997; *Cook et al.,* 2000; *Jain and Lall,* 2000].

High and low streamflow regimes: Probability changes and regional hydroclimatic response

Three 31-year periods illustrating high and low streamflow regimes were examined for multidecadal time scale analysis (low: 1830-1860, 1870-1900; high: 1901-1931). These periods are noteworthy for the persistence of low and high flow, and for the fact that low flow periods of this magnitude are not found in the 20th century. Also evident are the qualitative differences in the flow sequences that constitute these three 31-year high/low streamflow periods. Indeed, if we examine the empirical probability density functions (*pdf*) for these flow regimes[1], significant differences are seen in the tail probabilities (Figure 2). Using the full record (1703-1987) as the baseline, we find that the two low-streamflow periods have heavier left limbs, confirming the temporal shift towards higher

[1] Empirical probability density estimates are computed based on a nonparametric kernel density estimator with a normal optimal smoothing parameter [*Bowman and Azzalini,* 1997].

probabilities for low flows. However, the low flow regimes differ in the manner with which low flow probabilities redistribute within the 31-year periods. During 1870-1900, the flow variations were marked by an overall *pdf* shift towards low flows, with enhanced probabilities associated with the left limb of the *pdf*. In contrast, the 1830-1860 period was characterized by an increase in the more severe low flows, but with only slightly lower average flows than the full record. This suggests an increased variance in the flow and a non-uniform shift in the flow probabilities across different thresholds. The *pdf* for the wet period (1901-1931) shows a shift towards higher flows and heavier right limbs of the regime *pdf*. Again, only a part of the *pdf* (i.e., high flow probabilities) is outside the baseline variability band.

From the standpoint of gauging the water resources vulnerability, are mean flow anomalies adequate metrics? Given the apparent threshold-sensitive variations in the flow probabilities, the answer appears no. Indeed, if we examine the variations in the key flow thresholds (10^{th}, 33^{rd}, 67^{th}, and 90^{th} percentiles), the differences in the variability and severity within the multidecadal regimes becomes more evident (see Figure 2, inset). As noted above, the increased variance and skew in the flow distribution is quite evident for the 1830-1860 period. Also, the middle tercile (33^{rd} – 67^{th} percentile range) is wider for the 1830-1860 period, as compared to the 1870-1900 period. The temporal shifts in probabilities are seen quite well for the two low flow regimes, with the median (50^{th} percentile) flows during 1830-1860 nearly equaling the upper tercile (67^{th} percentile) flows during the 1870-1900 period. This reinforces the view that hydrologic variations at multiple time scales do not necessarily engender shifts in the entire *pdf;* a reorganization of flow exceedance probabilities across various thresholds is perhaps a better way to understand behavior of hydrologic regimes. These non-uniform shifts in the probabilities at interannual-to-interdecadal time scales have direct implications for the water resources management strategies, as will be further discussed later in the paper.

An examination of the temporal variations in the streamflow *pdf* is shown in Figure 3. The fluctuations across key flow thresholds during the low and high streamflow periods give a detailed description of the range of variability archived by tree rings. Note particularly that the persistent low flow events (10^{th} percentile) are simply not represented in the 20^{th} century instrumental record. For example, during 1830-1860, although the entire *pdf* shows a shift towards lower streamflows, the 10^{th} percentile shows the greatest sensitivity – as compared to the Q_{10} (10^{th} percentile flow threshold; exceeded 90% of the time) based on full record, flows during this period at the Q_{10} level are exceeded only 75% of the time. This provides a basis to assess the flow regimes in the context of severity and quantify the temporal changes in hydrologic risk.

The longer-term perspective on streamflow excesses and deficits reflects the regional expression of climate variations and change. Although no mechanistic explanation for the past climate variations and change is proffered, it is useful to examine the spatial scales associated with the multidecadal flow variations. Figure 4 shows the Palmer Drought Severity Index (PDSI) [*Cook et al.*, 1999] anomalies for the three low and high flow regimes discussed above. On these multidecadal averaging scales, there appears to be a remarkable degree of spatial coherence during the 1901-1931 wet period. Similarly, the 1870-1900 dry period shows a southwest US drought extending to the intermontane and central US region. The 1830-1860 dry period is characterized by a higher variability (see Figure 2, inset). Wet in some years, it also contains the most persistent and intense low flow period (mid-1840s through the late 1850s) in the full 285-year record. Although, the dry conditions were extensive in some of these years (1842, 1845-47, 1855-56), persistent drought conditions were restricted in spatial extent, with a core area in eastern Colorado [*Woodhouse et al.,* 2001]. This observation of a dry period is also supported by the limited documentary evidence of increased eolian sand dune movements (most likely related to drought and high temperatures) from the 1840-1870 period over the western Great Plains [*Muhs and Holliday*, 1995]. The composite PDSI (Figure 4) for 1830-1860 period indicates the less widespread nature of this dry period, with an extension of dry conditions into parts of the Great Plains. Overall, it seems clear that persistent and severe droughts have been a feature of the 19th century. This evidence provides a compelling perspective for reassessing the adequacy of current water resource management and planning infrastructure.

Discussion: Implications for water resources vulnerability

The vulnerability of water resources systems stems from: (a) the variable and uncertain nature of water supply, primarily stemming from hydroclimatic variations and change, and (b) the rapidly evolving nature of regional water demand, due to population growth, recreation needs, hydropower, agriculture, and mandatory water allocation for stream and riparian ecosystems. Thus, there is a need to reassess the existing multi-objective water resources management and planning framework. In this context, the results presented here are relevant for a number of emerging vulnerability issues:

1. The analysis of a long streamflow record showed that the reliability of water supply is contingent upon the nature of hydrologic regime. On water resources planning and management time horizons (typically 30-50 years), an understanding of multidecadal streamflow variations is necessary to devise robust planning and operations strategies. Furthermore, the temporal

changes in flow probabilities are threshold-sensitive – the severity of the multidecadal flow excesses and deficits are thus quite sensitive to the different "flavors" of the low and high flow regimes. Consequently, the ability of a reservoir storage to provide reliable water supply depends both on the scales of variability embedded in the limited-length flow record used for design, and the nature of flow probabilities (as seen in the empirical *pdf*). We illustrate this using a hypothetical water resources system, operating on contiguous 30-year flow segments from the reconstructed streamflow. The design mean flows (Q_{wy}) are based on the "wet" 1901-1931 record. Although this exercise is purely illustrative, the basis for using the early 20th century period is motivated by the fact that a majority of reservoir systems in the West were designed during this period (Figure 5). We allow the reservoir storage to be at Q_{wy} (integrated flow during one mean water year). The water demand is considered at three levels: 0.85 Q_{wy}, 0.9 Q_{wy}, and 0.95 Q_{wy}. A 30-year sliding window is used to assess the reservoir performance. The reservoir performance is assessed based on the ability to deliver the prescribed demand over a 30-year period (i.e., shortfall frequency is based on the fraction of years that the annual demand is not met). We find that the multidecadal low flow regimes (1830-1860, 1870-1900) exhibit major episodes of system vulnerability. Indeed, this allows us to tie the multidecadal flow regimes and temporal changes in the *pdf* to potential impacts on managed water resources infrastructure. Higher demand levels serve to increase the systems' inability to cope with flow deficits and the inadequacy of the significant storage considered here.

2. Analysis of the 19th century streamflow variations suggests the occurrence of severe and persistent droughts. In the future, such flow deficits coupled with present and future levels of water demands may inflict significant stress on the water-dependent sectors. Also noteworthy are the spatial scales of the 19th century droughts. For example, the very broad regional scale of the 1870-1900 low flow period may lead some of question the efficacy of mechanisms such as interbasin water transfers to alleviate water shortages. In view of the observed nature of multidecadal hydrologic variability, innovative adaptive strategies must reassess management practices and hedging strategies that consider the temporal variations in hydrologic risk. Although, it is important to stress the limitations inherent in the proxy-based reconstruction used here, it is nonetheless clear that the diagnosed water deficits on multidecadal time scales, with large spatial signatures have important vulnerability and policy implications.

3. Overlapping spatial scales of climate variability and river basin provide a natural avenue for probing the potential stresses exerted by regional and global climate change on water supply. The results presented here analyzed a paleo-environmental record to understand and assess the range of past hydrologic variations and

their potential impacts on water resources in the interior western United States. The wider range of flow variations and the characteristic spatial scales diagnosed here also point to the complex nature of regional hydrologic response to climate. Consequently, in contrast to the broad-scale model and proxy-based assessment strategies employed for understanding temperature and precipitation sensitivity to climate variations and change, regional-scale hydrologic vulnerability is likely better understood by developing river basin-specific reconstructions and models that distill both the multiscale large-scale climate signal, as well as capture the basin-scale surface hydrologic variability.

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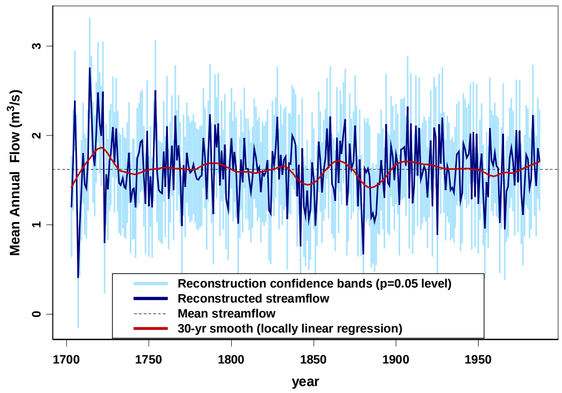

Figure 1. Reconstructed water year (October-September) flows for the Middle Boulder Creek, Colorado. The 30-year smoothed estimate (based on robust locally weighted regression [*Cleveland*, 1979]) shows the range of flows associated with multidecadal low (1830-1860, 1870-1900) and high (1901-1931) streamflow regimes. The increased variability in the early part of the reconstruction, from 1703-1730, in part is due to the smaller sample size as compared to the rest of the record. The confidence bands are based on the root mean squared error estimates from the verification period.

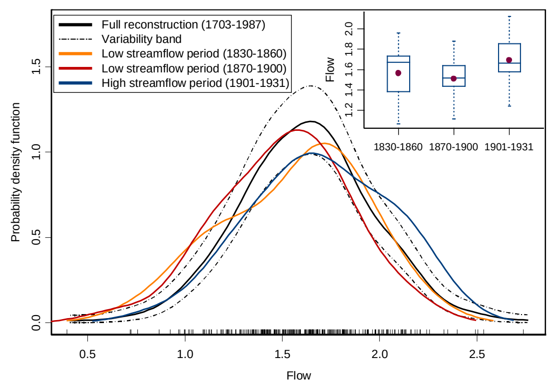

Figure 2. Comparison of the empirical probability density functions for the wet and dry regimes seen in the reconstructed Middle Boulder Creek streamflow. The dashed lines correspond to the variability bands [*Simonoff*, 1996] – quantifying the inherent variability associated with the density estimation; the density estimation is based on optimal normal bandwidth [*Bowman and Azzalini*, 1997]. The three regimes show anomalously heavy tails (at different flow thresholds). *(inset)* The boxplots show the relative range of variations for the three regimes. The boxes correspond to the 33rd, 50th, and 67th percentile. The whiskers extend to cover the 10th and 90th percentile. Mean flow during the low and high streamflow regimes are shown by red dots. The reader may note that the differences in the historical and reconstructed flows limit a direct interpretation of the implications of *pdf* variations for the instrumental record. An analysis of the differenced time series (for the 1912-1987 historical and reconstructed flow) revealed that the *pdf* of this "error" distribution has a mean = 0.07, standard deviation = 0.24.

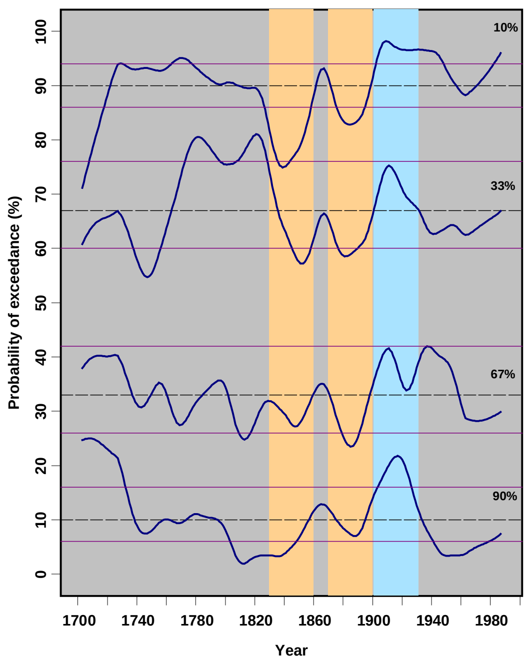

Figure 3. Evolutive empirical probability distribution for the reconstructed water year (October-September) flows at Middle Boulder Creek, Colorado. Long-term variations in the 10^{th}, 33^{rd}, 67^{th}, and 90^{th} percentiles were estimated using the robust locally weighted regression [*Cleveland*, 1979] of a threshold exceedance process with a 50-year moving window. The percentile estimates from the full record (1703-1987) that correspond to the threshold exceeded (dashed lines) and the bootstrap-based confidence bands ($p = 0.1$, 0.9 level) for the individual flow threshold are also shown (red lines). The regression estimates at the beginning and end of the reconstruction have somewhat limited interpretability, due to higher variance. Trends and variations in the individual flow thresholds reflect the multidecadal streamflow regimes and their severity, as indicated by excesses and deficits across the flow thresholds.

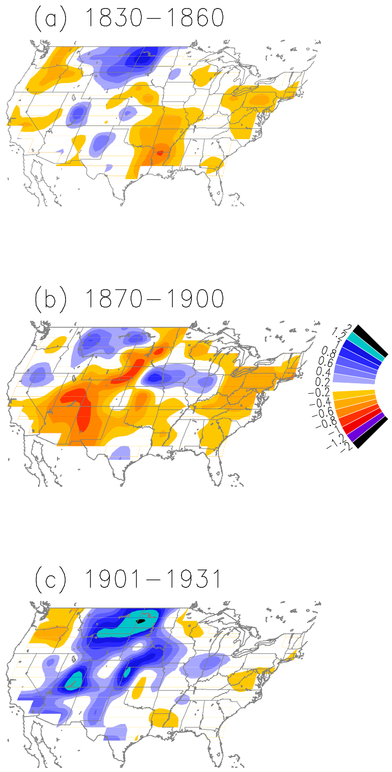

Figure 4. Composite PDSI anomalies corresponding to the diagnosed multidecadal streamflow regimes. The 1700-1978 PDSI reconstruction used here is based on 154 grids spanning the conterminous United States [*Cook et al.*, 1999]. For the Colorado region, the mean and standard deviations for the three period are noted in the parenthesis: 1830-1860 (-0.07, 1.8), 1870-1900 (-0.61, 1.4), and 1901-1931 (0.352, 1.44). Note that the highly localized PDSI anomalies exceeding a magnitude of 1.2 are shown using a single color code.

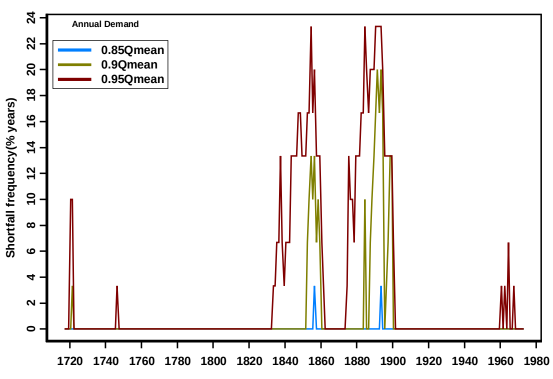

Figure 5. Analysis of water resources system vulnerability to hydroclimatic variations based on a hypothetical reservoir model. Mean flow (Q_{wy}) is determined from the “wet” 1901-1931 period. Three levels of water demand are considered - 0.85 Q_{wy}, 0.9 Q_{wy}, and 0.95 Q_{wy}. The reservoir system is forced using 30-year contiguous segments of the reconstruction (for example, 1703-1732, 1704-1733 etc.) to assess the impact of multidecadal streamflow variations and the adequacy of the reservoir for the three levels of water demand.